

Wind field effect on hydrography and chlorophyll dynamics in the coastal pelagial of Admiralty Bay, King George Island, Antarctica

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Abstract: The vertical distribution of physicochemical parameters and Chl *a* at a fixed station in Admiralty Bay (King George Island, South Shetland Islands) was recorded over 73 days during the summer of 1988/89. Temporal variations in Chl *a* and nutrient stocks in the euphotic zone were associated with changes in the wind/hydrological regime. Northerly winds of late December and early January moved the surface layers towards the outer bay, during which time the chlorophyll stocks remained low in the euphotic zone. Turbulence induced by southerly winds in the second half of January resuspended sediments and benthic diatoms in the shallow (0–20 m) inner inlets of the bay, increasing turbidity and nutrient concentrations at the surface. During the first half of February wind relaxation caused the mass sedimentation of previously resuspended benthic diatoms increasing chlorophyll and phaeopigments in the subsurface layers in deeper sections of the bay. Although turbulence limits phytoplankton biomass accumulation in open waters of the Antarctic, it may have a positive effect (increasing chlorophyll biomass of benthic origin) in coastal pelagic environments during late summer.

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Key words: wind field, hydrography, upwelling, chlorophyll, nutrients, benthic diatoms

Introduction

Despite optimum incident light and nutrient regimes during spring/summer periods, deep offshore waters around Antarctica are constantly subjected to strong wind-induced turbulence which limits phytoplankton development by increasing the depth of the mixing zone in relation to that of the euphotic layer (Hart 1934, Sakshaug & Holm-Hansen 1984, Priddle *et al.* 1986, Mitchell & Holm-Hansen 1991). Wind has also been reported to limit plankton biomass in sheltered areas as well (Hart 1942, Chojnacki & Weglenska 1984, Lipski 1987, Clarke *et al.* 1988, Mitchell & Holm-Hansen 1991), although the effects of the wind field on ecosystem dynamics in coastal areas during summer have been poorly investigated.

The characteristics of spring/summer blooms (starting period, magnitude, duration, etc.) in Antarctic coastal environments may change according to the hydrographic regime associated with the local wind field. Apart from wind-induced upwelling which affects the physical and chemical characteristics of nearshore water, turbulence generated by strong winds can have a positive effect on chlorophyll *a* (Chl *a*) accumulation in the water column by resuspending benthic diatoms. This is very common in the sediments of Antarctic embayments (Platt 1979, Wägele & Brito 1990).

In this paper we describe the seasonal changes of hydrographic parameters in relation to the wind regime, and how this increases Chl *a* stocks in the water column in late summer.

Study area

Admiralty Bay (62°03'–12'S, 58°18'–38'W) is a fjord-like embayment on King George Island, South Shetland Islands, with an area of 122.08 km² and c. 24 km³ of water (Rakusa-

Suszczewski *et al.* 1993). Fig.1 shows the general bathymetry of the bay and the marginal shelves of the inner inlets of <50 m depth. Water exchange with the Bransfield Strait takes place along the deep (>500 m) entrance channel, through tidal currents and wind-induced transport (Pruszek 1980).

Chl *a* concentrations during early summer periods are usually below 0.5 µg l⁻¹ (Pruszek 1980, Lipski 1987), due to turbulence and rapid exchange of water with the Bransfield

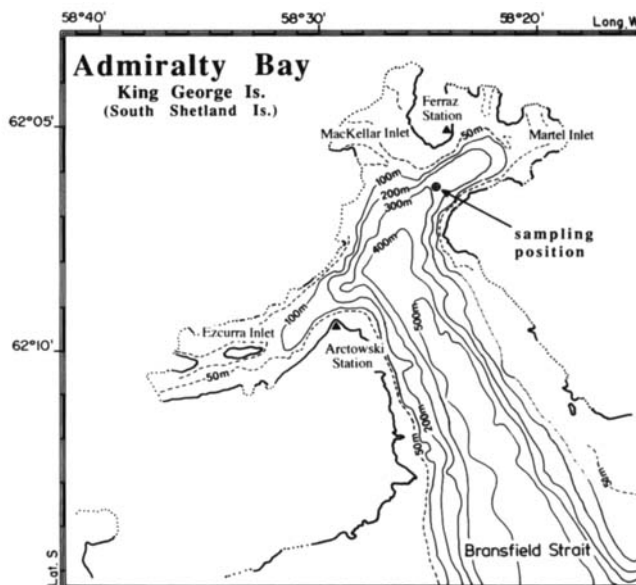


Fig. 1. Map of Admiralty Bay showing bathymetry and position of sampling station. Dotted lines indicate areas of glacial ice.

Strait induced mainly by westerly and northerly katabatic winds, which are more frequent during warmer seasons (Nowosielski 1980, Pruszek 1980). According to Pruszek (1980) these winds cause the outflow of surface layers towards the Bransfield Strait, leading to upwelling in the inner inlets. Maximum chlorophyll concentrations are reported in late summer (February/March), and in most cases in subsurface layers (Tokarczyk 1986, Lipski 1987). The dynamics of such late summer subsurface chlorophyll accumulation still needs to be investigated.

Material and methods

Sampling strategy

From 19 December 1988 to 7 March 1989 water samples were taken from the upper 50 m at a fixed station in Admiralty Bay, over an c. 300 m water column, located less than one nautical mile off the Brazilian Station "Comandante Ferraz", at the entrance to Martel Inlet (Fig. 1). Physical and chemical parameters measured here represent the mean hydrographic features in the deeper parts of the central bay. Sampling was usually conducted at weekly intervals or twice a week when wind conditions were favourable. A hand winch was used to lower a Van Dorn type water sampler from an inflatable boat, to 50 m.

The depth of the euphotic zone at the sampling point was initially estimated from Secchi disk readings. Water samples were taken from eight depths (0, 2.5, 5, 10, 20, 30, 40 and 50 m), and the temperature of each was read immediately by introducing a standard thermometer into the Van Dorn bottle. Two subsamples of 100 ml representing each depth were immediately fixed with 1 ml of buffered formalin (0.4% final concentration), and with 2 ml of phenol/ethanol solutions for later microscopic and ammonium analyses, respectively. The remainder water was transported to the laboratory of Ferraz Station in 5 l polyethylene bottles for analysis of nutrients, salinity, Chl *a* and phaeopigments.

Vertical net-samples (50 μm mesh) were taken on each sampling day, from 50 m to the surface, in order to determine the microplankton species composition.

Laboratory work

In the Ferraz Station laboratory, subsamples were taken from bottles for salinity, nutrient and pigment analyses. Salinity was calculated from measurements of conductivity using the conversion factors of Damasceno *et al.* (1989). The nutrients nitrate, nitrite, phosphate and silicate were determined photometrically according to Strickland & Parsons (1972). Ammonium was analysed according to Liddicoat *et al.* (1975) with modifications regarding the conditions of colour development; samples were incubated in the dark for 24 h at 30°C.

Two hundred ml of seawater were filtered through Whatmann GF/F filters for Chl *a* and phaeopigment analyses (Evans &

O'Reilly 1983). Samples were occasionally prefiltered through a 10 μm Nitex mesh for measuring the concentration of pigments in the <10 μm size fraction. Filtration was always carried out under low vacuum pressure (<200 mm Hg). The filters were dried and maintained in the dark at -15°C for less than three months, when the fluorescence of 90% acetone extracts was measured with a Turner 111 fluorometer according to Strickland & Parsons (1972).

For the Utermöhl (1958) analyses, formalin-preserved water samples were stained with Rose Bengal to enable the nanoplankton to be more easily distinguished, and 50 ml were sedimented for 48 h; a Zeiss inverted microscope was used for counting cells of the nano- and micro size fractions under phase contrast, in half-chamber area (alternate transects), with a magnification of x 130. The nano-size categories of 1–3, 3–6, 6–12 and 12–20 μm were counted with an oil immersion objective in calibrated sectors of cross diameter transects, with magnification of x 800. The net samples were fixed with 2% (final concentration) buffered formalin and analysed for species composition with the standard microscope.

Air temperature and wind data (speed, direction) were measured by an automatic station operated at Ferraz by the National Institute for Space Research (INPE). The station did not operate from 29 January to 3 February, but the meteorological conditions were stable during this period (personal observation of the authors). Visual observations of wind and sea conditions were performed daily. Drifting shore ice and growlers were also used as tracers for measurements of surface current velocity.

Results

Meteorological regime

The wind field during the sampling period has been plotted in the form of stick vectors based on daily measurements of wind speed and direction (Fig. 2). Five different periods of wind conditions are discernible: I) in late December (19–29) winds were predominantly northerly and northeasterly (i.e., of south and southwest directions, respectively) and usually <10 m s^{-1} ; II) from December 30 to January 16, northerly winds predominated. They were persistent and strong enough to generate upwelling in Martel and MacKellar inlets, as proposed by Pruszek (1980). The drifting of small pieces of shore ice and surface water towards the entrance of the bay followed the wind direction; III) on 17 January the wind field changed completely with winds originating from the south, gusting persistently to 24 m s^{-1} until the end of January; IV) in the first two weeks of February, the winds were irregular with moderate to low speeds (max. 10 m s^{-1}), between 12 and 15 February there was no wind; V) during the second half of February winds were again northerly and occasionally stronger than 10 m s^{-1} , again generating upwellings in Martel and MacKellar inlets.

Air temperatures varied according to wind directions. Positive values were usually associated with northerly winds bringing warm air masses from lower latitudes, whereas

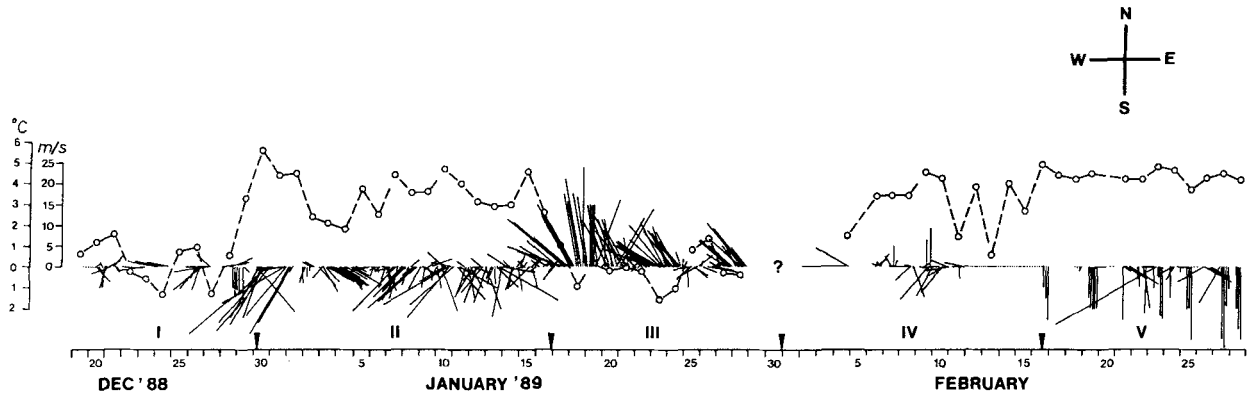


Fig. 2. Wind field in Admiralty Bay between 19 December 1989 and 28 February 1989. Dashed line represents mean daily air temperature. Roman numerals indicate periods of different wind conditions.

negative values coincided with southerly winds bringing colder air from the south. This is consistent with the observations of Nowosielski (1980), indicating that the wind field measured inside the bay is a reflection of the large scale atmospheric patterns which are not totally perturbed by the lee effect of headlands around the bay.

Hydrography

Secchi disk readings varied from 2.5–10.5 m according to the wind field (Fig. 3). The maximum depth of the euphotic layer in the bay expected from these values for non-turbulent periods, would be c. 30 m. This is consistent with the mean summer value of 23 m reported by Lipski (1987) during his annual cycle studies in the bay.

Mean water temperature in the upper 50 m varied from 0.5–1.8°C (Fig. 4a), with negative values at the beginning of the study, increasing gradually throughout the season. Thermal stratification was only observed in the upper 10 m following short periods of wind relaxation. A maximum of 3°C was measured at the surface on 16 January.

Surface salinity was lowest in late December due to intense melting of snow and glacial ice. During most of the season, however, salinity was around 34‰ with short term (2–3 days) stratification in the upper layers (0–10 m), due to increased inflow of freshwater from melting snow during short periods of stable meteorological conditions. This was observed for instance between 19–22 December, 3–6 January, 16 January and 2 March, as indicated by arrows in Fig. 4b.

The gradual recovery of nutrient pools at surface, especially nitrate, ammonium and silicate, was indicative of wind induced upwelling in the inner inlets of the bay. Phosphate varied from 1.69–2.34 μM (Fig. 4c) with slightly lower values in December and during early January. From late January until the end of the study period concentrations fluctuated around 2 μM . The pattern of temporal variations in the upper 10 m showed three short periods of stratification with low concentrations at the surface during periods of low wind ($<5 \text{ m s}^{-1}$). Between 6–8

February an inverse stratification with higher concentrations at the surface was noted. The temporal variation in nitrite concentration was very similar to that of phosphate, showing stratification during the same periods, and varying from 0.06–0.19 μM , with no remarkable changes throughout the sampling period (Fig. 4d). Nitrate varied from 9.7–36.7 μM (Fig. 4f), short-term variations at the surface were not related to the wind regime and the general long-term variation was similar to that observed for silicate, with low initial values in late December increasing gradually throughout the season. Mean concentrations in the water column decreased temporarily during the first week of February but increased continuously thereafter reaching maximum levels in early March. Ammonium varied from <0.1 –1.35 μM (Fig. 4e), concentrations were higher in the water column during the stable (and melting) days of late December and during the upwelling periods of January as well, decreasing to undetectable levels from 30 January to 16 February

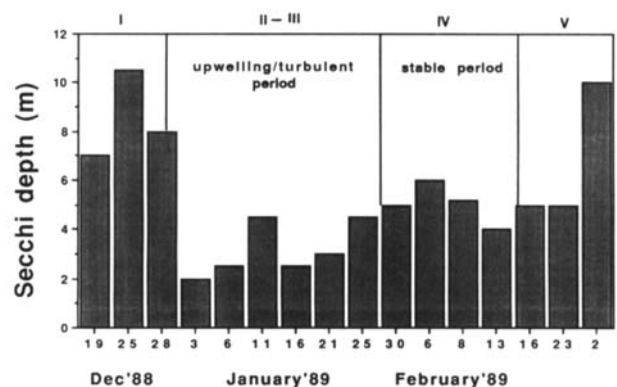


Fig. 3. Temporal variation of water transparency at the sampling station in Admiralty Bay, during summer 1988/89. Roman numerals indicate periods of different wind conditions.

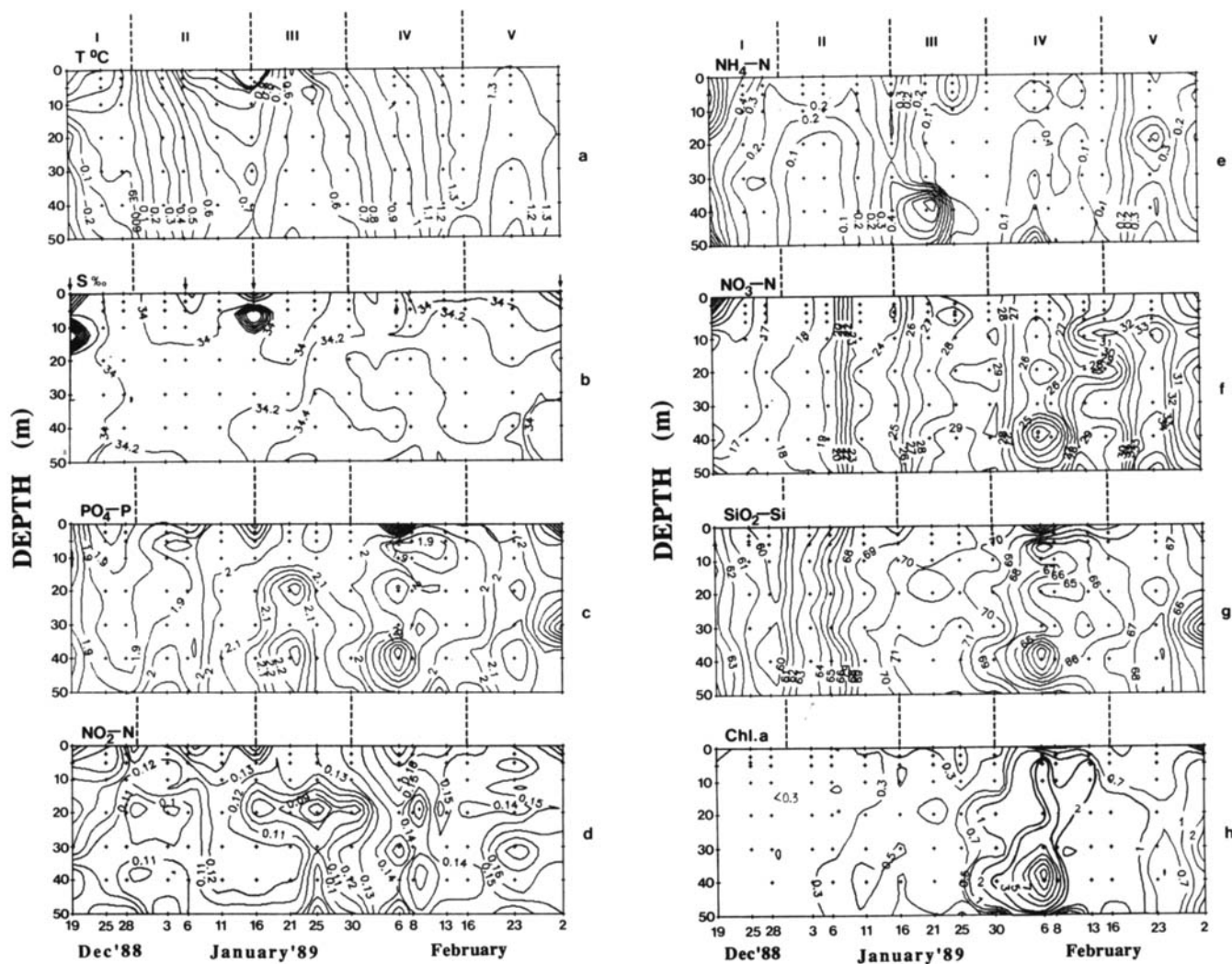


Fig. 4. Temporal variation of temperature, nutrients and Chl *a* in the upper 50 m at the sampling station in Admiralty Bay, during summer 1988/89. Nutrients in μM and Chl *a* in $\mu\text{g l}^{-1}$. Vertical arrows on the salinity plot (b) indicate periods of high freshwater input; the dilution of seawater also affected the vertical distribution of phosphate (c) and nitrite (d).

and increasing again following the second upwelling period.

Silicate varied from $58.3\text{--}73.5 \mu\text{M}$ (Fig. 4g), the vertical distribution was homogeneous and concentrations increased gradually between 19 December and 25 January, particularly from early January (i.e., upwelling period). At the beginning of February, concentrations were stratified with low levels at the surface and between 20 and 40 m.

Chlorophyll a and phytoplankton

During windy and turbulent periods of January, total Chl *a* was distributed homogeneously in the upper 50 m with concentrations usually below $0.3 \mu\text{g l}^{-1}$, occasionally reaching $0.5 \mu\text{g l}^{-1}$ below the surface (Fig. 4h). On 25 January, concentrations in the micro-size fraction started to increase rapidly, but only in the lowest levels of the euphotic zone. By 6 February concentrations in the euphotic zone varied between 0.5 and $3 \mu\text{g l}^{-1}$, with a single

maximum of $17.9 \mu\text{g l}^{-1}$ occurring at 40 m; two days later, however, this had fallen considerably. Most of the chlorophyll-biomass at deeper levels of the euphotic zone was concentrated in the micro-size fraction, whilst the nano-size fractions contributed up to $2.4 \mu\text{g l}^{-1}$, i.e. 70% of the total Chl *a*, at 10 m. Mean water column Chl *a* concentration decreased following the second upwelling period (16–28 February), but were still higher than during the upwelling/turbulent periods of January. On 2 March concentrations in the euphotic zone were lower than the previous stable period, with high concentrations of 4.3 and $4.0 \mu\text{g l}^{-1}$ being measured at 30 and 50 m respectively.

Phaeopigments were low in the whole water column during the upwelling period but increased slightly during the turbulent period of late January, and remarkably during the stable periods of early February.

The quantitative microscopic examinations showed that two distinct unicellular plankton assemblages were present

throughout the study period. Fig. 5 shows the average concentrations (eight depths) of the most representative groups in the water column from the surface to 50 m. Two periods may be distinguished from differences in species composition: i) from late December to 21 January (i.e. upwelling period), a typical summer community was present, dominated by flagellates and monads of $<6 \mu\text{m}$. Heterotrophic dinoflagellates (mainly *Gymnodinium* and *Gyrodinium* spp) and ciliates were always present but at densities of less than 1000 cells l^{-1} (data not shown). Pelagic diatoms (*Chaetoceros tortissimus* and *Thalassiosira tumida*) were also observed but they formed an insignificant fraction of the phytoplankton. By 25 January, the species composition of autotrophic cells had changed completely. It was almost totally dominated by chains of pennate diatoms (*Licmophora*, *Navicula* and *Nitzschia*) which occupied the water column down to 50 m. These species were very abundant in the intertidal zone around Martel Inlet (authors' observations), dominating the autotrophic microplankton until 30 January from 5 m downwards. Conversely, pelagic species and flagellates were dominant at the surface. On 30 January a very dense layer of these species was detected at 40 m reaching bloom levels with over than three millions cells l^{-1} . For this reason the mean value estimated for the water column rose to 420 000 cells l^{-1} . Unfortunately, the Utermöhl samples of 6, 8 and 16 February were lost accidentally but the examination of net-samples showed that the same species of benthic diatoms were very abundant during the periods of maximum Chl *a* concentrations in the first half of February and on 2 March. From 18 February to the beginning of March *Chaetoceros tortissimus*, *C. socialis*, *Thalassiosira tumida* and *Nitzschia* spp, dominated the surface phytoplankton.

Discussion

Nutrients vs. the wind-induced hydrographic regime

Summer values of temperature, salinity and nutrients observed in the present investigation are similar to those reported previously (Pruszek 1980, Lipski 1987). The temporal series revealed vertical homogeneities in these parameters during upwelling/turbulent periods interposed by short-term stratification which developed in the upper 10 m during 2–3 day period of low winds. This was particularly clear in the cases of nitrite and phosphate, in which lower concentrations at the surface followed the decrease in salinity. Hence, they can be mainly attributed to dilution by intense melting of glaciers (Lipski 1987, Prego *et al.* 1989). In fact, mean air temperatures were much higher during these periods due to northerly winds. The lower nitrate concentrations at the surface at the beginning of the study period may also be attributed to dilution due to melting of glaciers and higher fresh water inputs into the bay.

Phytoplankton uptake also decreased surface nutrient concentrations, but to a much lesser extent since the autotrophic biomass was too small to take up measurable amounts of nutrients in the 2–3 days of stable conditions between the

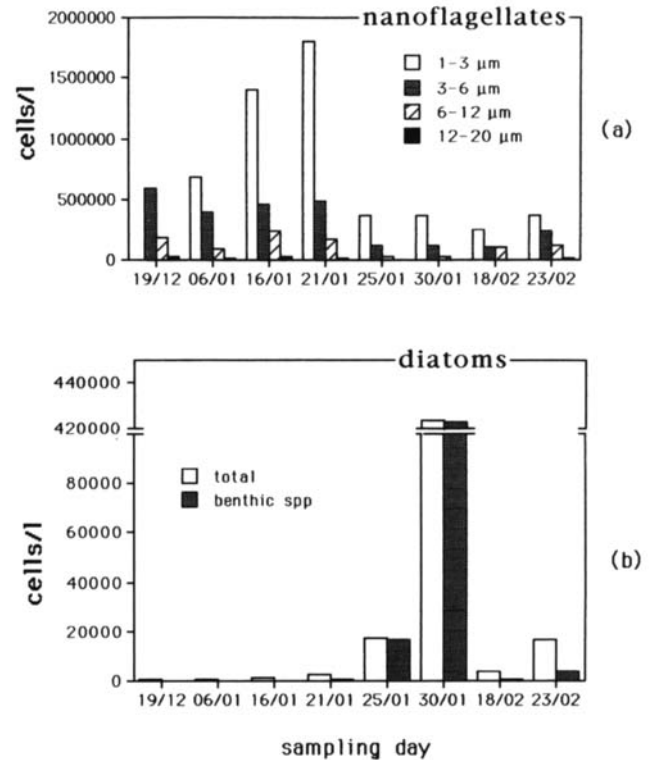


Fig. 5. Changes in the average number of dominant phytoplankton at the sampling station in Admiralty Bay, during summer 1988/89. Bars represent the arithmetic mean of the eight values obtained at each depth from surface to 50 m.

upwelling events. However, nutrients decreased with depth on 6 and 8 February, suggesting more consumption in the deeper levels of the euphotic zone where the bulk of Chl *a* was concentrated. Moreover, if the euphotic zone is extended down to 0.1% of surface light, as suggested for Antarctic waters (El-Sayed & Turner 1977, Holm-Hansen *et al.* 1977), the great autotrophic biomass accumulated at 40 m would have contributed for the higher depletion of nutrients at these depths between 30 January and 6 February (see Fig. 4c, f and g). Photoinhibition of phytoplankton in the surface layers was mentioned by Lipski (1987) and could account for a lower uptake of nutrients, leading to higher concentrations at the surface when compared to further down the euphotic zone.

On a seasonal scale, nitrate and silicate were best indicators of upwelling, increasing in the upper layers of the bay following persistent northerly winds, especially between 1 and 11 January. Temporal trends of ammonium clearly followed the wind/hydrographic regimes, increasing during turbulent periods and decreasing during stable periods.

Although terrestrial sources of ammonium from bird and mammal colonies have been reported to increase the surface pool of reduced nitrogen in Antarctic coastal waters (Tatur & Myrcha 1983, Dawson *et al.* 1985, Perissinotto & Duncombe Rae 1990), in Admiralty Bay they are concentrated at Llano Point, near Arctowski Station, c. 10 km to the west of our

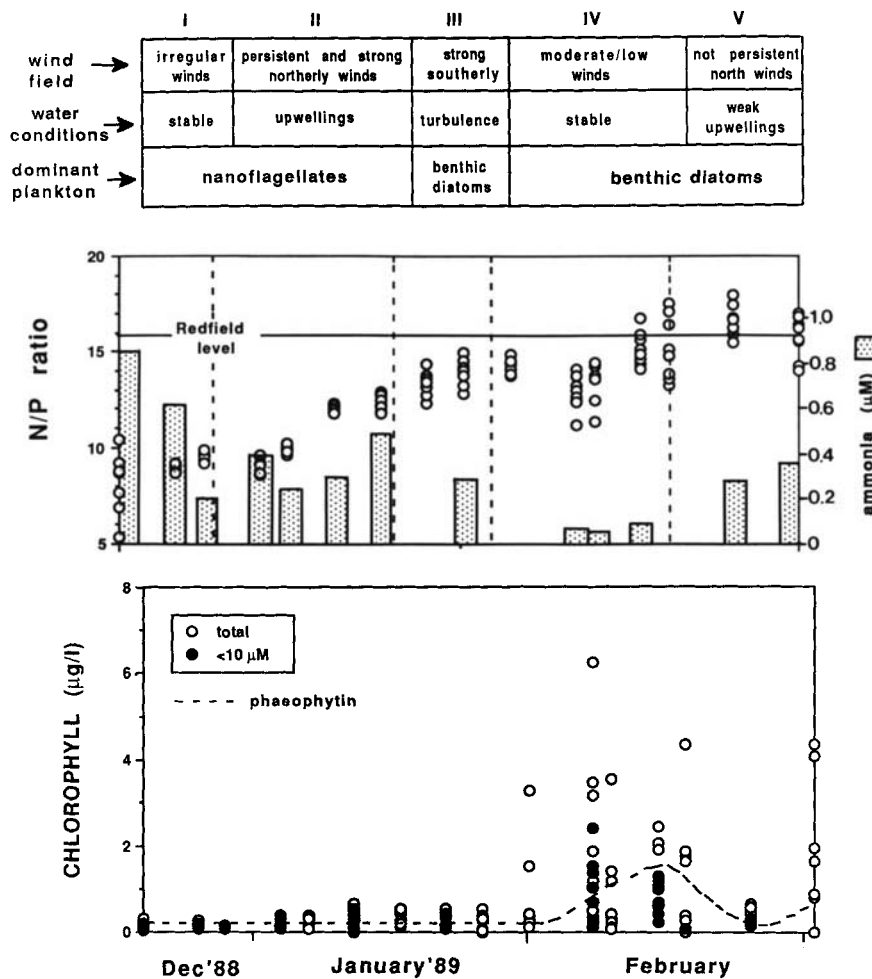


Fig. 6. The dynamics of Chl *a* accumulation in Admiralty Bay in relation to the wind and hydrographic regime, during summer 1988/89. The upper panel indicates the conditions of wind, surface water stability and dominant phytoplankton in the upper 50 m of the water column. The middle panel illustrates the increase of N/P ratio (open circles) and changes in surface concentrations of ammonium (bars). The lower panel shows the seasonal changes in Chl *a* (total and <math><10 \mu\text{m}</math> fraction) and phaeophytin concentrations. All points obtained in the upper 50 m are indicated for each sampling date except the $17.9 \mu\text{g l}^{-1}$ observed at 40 m on 6 February.

sampling position. In addition, Tatur & Myrcha (1983) reported that most of the ammonium produced there is lost to the atmosphere by volatilization, affecting concentrations in adjacent waters only during heavy rainfall. Therefore, the effect of these ammonium rich waters from penguin colonies on Martel Inlet is negligible, especially under the influence of northerly winds which would drive surface waters adjacent to the penguin rookeries towards the outer bay. Hence, the contribution of benthic communities to the euphotic zone seems to be considerable during turbulent periods. A well developed benthic community, formed by a number of invertebrates, fringes the internal shelves of the bay. According to Wägele & Brito (1990), the abundance of total invertebrates (mainly molluscs, isopods and ophiuroids) in the epi- and infauna of Martel Inlet can be higher than $70\,000 \text{ ind. m}^{-2}$ within the depth range of 3.5–25 m.

Although we did not measure ammonium flux at the sediment-water interface, it is generally accepted that such well developed communities regenerate high amounts of ammonium which may be carried upwards during upwelling/turbulent events, increasing the pool of reduced nitrogen in the euphotic zone.

The southerly winds between 17 and 30 January did not induce upwelling on the same scale as those generated by the northerly winds, but they were strong enough to generate

turbulence, resuspending sediments in the innermost and shallow (i.e., <math><25 \text{ m}</math>) areas of Martel Inlet, affecting water transparency throughout the whole bay area. Accordingly, on 21 January not only was the Secchi depth at the sampling station as low as during the previous periods of northerly winds before 17 January (Fig. 4), but also the number of benthic diatoms increased considerably on January 25.

The dynamics of chlorophyll accumulation in late summer

The patterns of temporal variation of Chl *a* were consistent with those reported previously (Szafranski & Lipski 1982, Tokarczyk 1986, Lipski 1987, Domanov & Lipski 1990). They also showed peaks of Chl *a* at subsurface depth in the water column during February. Lipski (1987) reported the maximum at 25 m in different areas of the bay, and Tokarczyk (1986) reported layers of maximum concentrations between 50 and 75 m throughout the bay.

Conditions which caused the late summer accumulation of Chl *a* at the sampling site during February 1989 are described in Fig. 6. During the intense upwelling events of January, Chl *a* concentration was low in the euphotic layer due to the rapid exchange of water with the Bransfield Strait. Nutrients increased

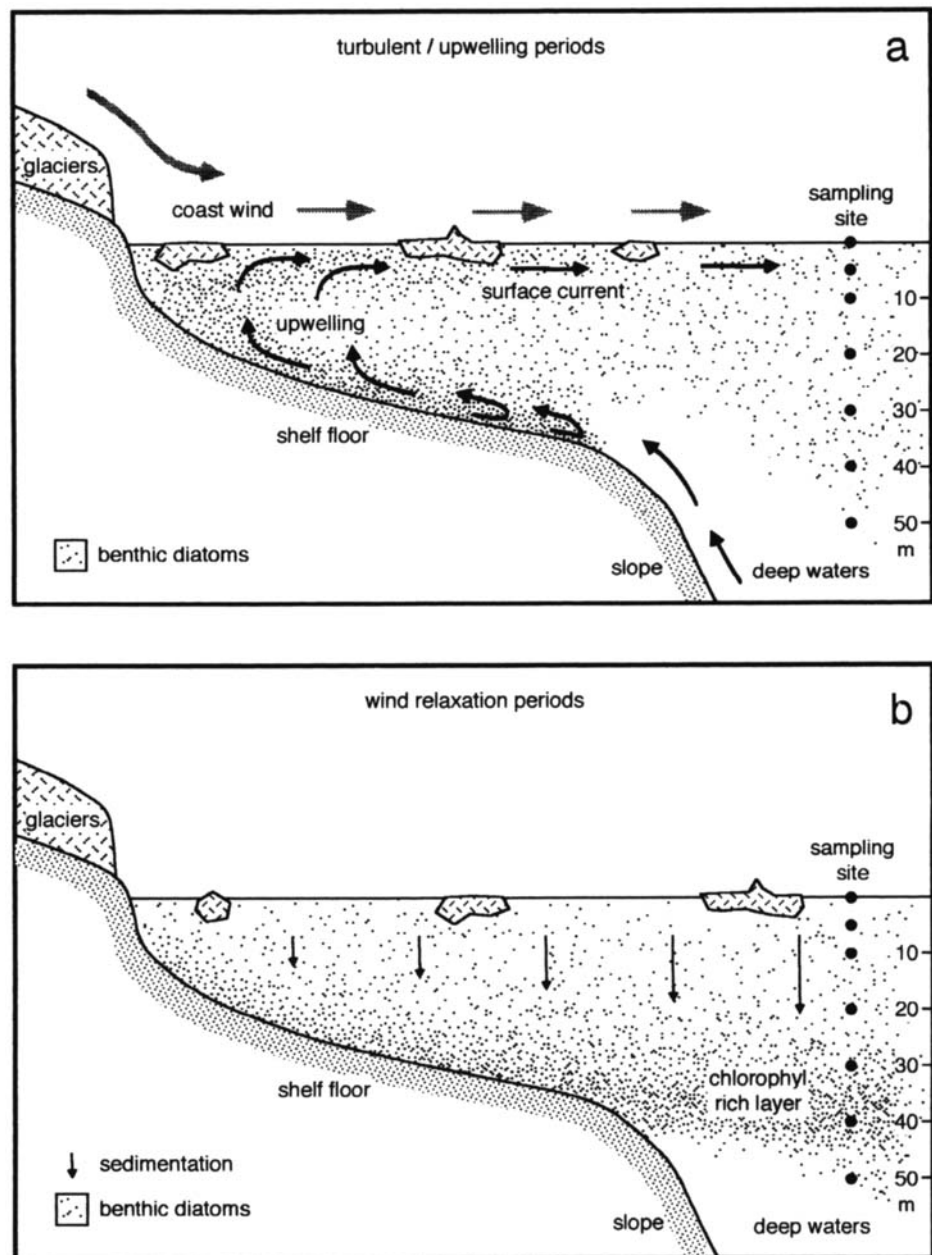


Fig. 7. a. Schematic representation of the resuspension of benthic diatoms during turbulent/upwelling periods from the shallow sections of the bay, and b. the subsequent sedimentation and accumulation at subsurface depths during wind relaxation periods.

rapidly due to upwelling, and ammonium was present in the surface layers. Surface phytoplankton consisted mainly of phytoflagellates of less than $10 \mu\text{m}$.

The strong turbulence generated by the southerly winds not only continued this processes of increasing nutrient levels, but also resuspended benthic diatoms from the sediments of the inner shallow sections of the bay. Following cessation of higher winds during the first two weeks of February, Chl *a* accumulates in the water column through two different processes:

1) The growth of phytoplankton in the euphotic layer. The optimum nutrient status in surface waters (N/P c. 16), with considerable amounts of ammonium, favoured the growth of nano-sized cells in the upper part of the euphotic zone, mainly at 10 m, contributing up to 70% of the Chl *a* stock.

At the beginning of the stable period (i.e. by the end of January), the mean Chl *a* concentration in the euphotic zone was already around $0.5 \mu\text{g l}^{-1}$. Assuming an average growth rate of 0.5 d^{-1} (Spies 1987, Sommer 1989), Chl *a* biomass in the euphotic zone should reach at least $4 \mu\text{g l}^{-1}$ after the first six days of water column stabilization, which agrees well with the range concentration ($0.22\text{--}3.48 \mu\text{g l}^{-1}$) observed in the upper 10 m.

Considering the Redfield relationships for nutrient uptake and a C:Chl *a* ratio of 50, reported to be adequate for the coastal zones along the Antarctic Peninsula (Clarke *et al.* 1988, Mitchell & Holm-Hansen 1991), the decrease in mean concentrations of nitrate ($3.6 \mu\text{M}$) and phosphate ($0.3 \mu\text{M}$) in the euphotic zone (c. 0–30 m) between 30 January and 6 February, would suggest an accumulation of 5.7 and $7.6 \mu\text{g}$

Chl a l^{-1} , respectively. These values are higher than the actual mean of $2.6 \mu\text{g } l^{-1}$ observed on 6 February, which may be an indication of losses due to grazing and sedimentation. On the other hand, an accumulation of only $0.9 \mu\text{g Chl } a l^{-1}$ would have been expected from the $2.4 \mu\text{M}$ decrease in mean concentrations of silicate, using the biogenic silica to POC molar ratio of 0.6 (Nelson & Smith, 1986, Tréguer *et al.* 1991) when diatoms dominate in Antarctic waters. The estimates from the decrease in nitrate and phosphate are similar but significantly higher than from silicate, as also reported by Clarke *et al.* (1988) in South Orkney Islands.

The discrepancies between nutrient uptake and chlorophyll accumulation suggest the predominance of a regenerated production (*sensu* Dugdale & Goering 1967) in the euphotic zone. This is consistent with the microscopic analyses which revealed the dominance of nanoflagellates in the uppermost layers of the euphotic zone during the Chl a accumulation period. Obviously, a much higher depletion of nitrate and silicate would have been expected at the surface if diatoms had been dominating.

2) The mass resuspension of benthic diatoms from the sediments of the shallow inner inlets during the previous upwelling/turbulent periods, the tidal or wind-driven lateral advection and the continuous sinking of benthic diatoms caused the accumulation of large amounts of Chl a between 30 and 50 m. This is illustrated in Figs 7a and b, representing the upwelling/turbulent and wind relaxation periods, respectively. The density field presented as sigma-T (Fig. 8) calculated from temperature and salinity data clearly demonstrates that during the stratified periods of February, a deep denser water mass which had upwelled along the bottom slopes of the inner bay, was dominating from 20 m downwards. The high concentrations of Chl a in deeper layers are clearly associated with this water mass, which certainly favoured the buoyancy and accumulation of benthic diatoms at these depths.

The higher concentrations of phaeopigments during the period of maximum Chl a accumulation also may be of benthic

origin, considering that phaeopigments are reported to be very abundant in sediments of the Antarctic embayments (Platt 1979). Grazing also contributed to the pool of phaeopigments in the water column but to a lesser extent, since the herbivorous macrozooplankton is always poorly developed inside the bay during summer as a result of turbulence (Chojnacki & Weglenska 1984).

In late February, Chl a decreased abruptly throughout the water column. Northerly winds predominated during this time, causing upwelling and increasing ammonium concentration at the surface. Apparently, they were not persistent enough for a complete exchange of water with the Bransfield Strait, which would have caused the decrease of Chl a concentration to the same low levels ($<0.5 \mu\text{g } l^{-1}$) observed during January. Since the outflow of water from the bay was more pronounced in the upper layers, Chl a and phaeopigments accumulated in deeper water during early February were still rotted between 30 and 40 m in early March, when maximum concentrations of $4 \mu\text{g } l^{-1}$ were observed.

Conclusions

Resuspension of benthic diatoms from bottom sediments due to wind-induced turbulence is common in tropical and temperate estuaries, significantly affecting the secondary production of adjacent waters (Seeliger 1982, Roman *et al.* 1983, Demers *et al.* 1987). Demers *et al.* (1987) reported winds stronger than 4 m s^{-1} causing resuspension of particles from the sediments of St. Lawrence estuary. In San Francisco Bay, high Chl a concentrations in the water column due to wind-driven resuspension of diatoms was reported by Cloern & Nichols (1985). The magnitude of resuspension in Admiralty Bay seemed to be much higher, considering the stress of the wind regime which, according to Nowosielski (1980), may reach mean velocities up to 15 m s^{-1} for long periods.

Wägele & Brito (1990), using SCUBA-diving in the bay to study the benthic community, found very thick mats of diatoms

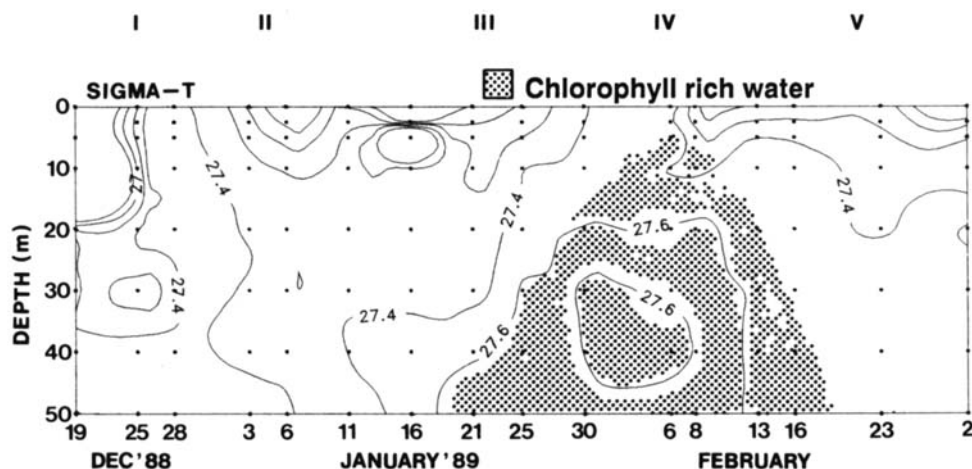


Fig. 8. Seasonal pattern of the density field (as sigma-T) in the upper 50 m, at the fixed station in Admiralty Bay during summer 1988/89. Roman numerals indicate wind periods of different wind conditions.

at 25 m (see their photographs number 7 and 8). Kopczyńska (1981) and Ligowski (1986) listed many benthic species in the phytoplankton collections of Admiralty Bay. Therefore, it seems that resuspension is frequent and affects the diversity of phytoplankton assemblages in the upper layers of the water column in such confined and shallow bays.

Although we did not provide direct evidence of resuspension of diatom resting spores from sediments, this may be an important mechanism of rapid build up of phytoplankton biomass during subsequent periods of wind relaxation. Resting spores of *Chaetoceros* and *Thalassiosira*, the dominant genera at the surface between 6 and 8 February, seem to be ubiquitous in Antarctic waters. They have been found around South Georgia (Fryxell *et al.* 1982), in sediment traps in the western Bransfield Strait (Leventer 1991) and in the Weddell Sea (Nöthig 1988), and also in Halley Bay sediments along the southeastern coast of the Weddell Sea (E. Nöthig, personal communication 1992).

We conclude that whilst in open waters wind-driven turbulence limits phytoplankton growth and Chl *a* stocks in the water column, in coastal areas it may have a positive effect regarding the accumulation of phytoplankton biomass and, consequently, affecting secondary production. This is especially true for sheltered coastal habitats in the Southern Ocean subjected to periodic upwelling/turbulence regimes.

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References

- CHOJNACKI, J. & WEGLENSKA, T. 1984. Periodicity of composition and vertical distribution of summer zooplankton (1977/1978) in Ezcurra Inlet, Admiralty Bay (King George Island, South Shetland). *Journal of Plankton Research*, **6**, 997-1017.
- CLARKE, A., HOLMES, L.J. & WHITE, M.G. 1988. The annual cycle of temperature, chlorophyll and major nutrients at Signy Island, South Orkney Islands, 1969-82. *British Antarctic Survey Bulletin*, No. 80, 65-86.
- CLOERN, J.E. & NICHOLS, F.H. 1985. Time scales and mechanisms of estuarine variability, a synthesis from studies of San Francisco Bay. *Hydrobiologia*, **129**, 229-237.
- DAMASCENO, R.N., GOMES, M. & ANDRÉ D.L. 1989. Uma metodologia para operacionalizar a condutividade como medida da salinidade. In *Resumos do I Simpósio Sobre Oceanografia, Instituto Oceanográfico*. São Paulo: Universidade de São Paulo, 64.
- DAWSON, R., SCHRAMM, W. & BÖLTER, M. 1985. Factors influencing the production, decomposition and distribution of organic and inorganic matter in

- admiralty Bay, King George Island. In SIEGFRIED, W.R., CONDY, P.R. & LAWS, R.M. eds *Antarctic nutrient cycles and food webs. Proceedings of the fourth SCAR symposium on Antarctic biology*. Berlin: Springer-Verlag, 109-114.
- DEMERS, S., THERRIault, J.C., BOURGET, E. & BAH, A. 1987. Resuspension in the shallow sublittoral zone of a macrotidal estuarine environment: Wind influence. *Limnology and Oceanography*, **32**, 327-339.
- DOMANOV, M.M. & LIPSKI, M. 1990. Annual cycle of chlorophyll *a* and primary production of phytoplankton in Admiralty Bay (Antarctica). *Polskie Archiwum Hydrobiologii*, **37**, 471-478.
- DUGDALE, R.C. & GOERING, J.J. 1967. Uptake of new and regenerated forms of nitrogen in primary productivity. *Limnology and Oceanography*, **12**, 196-206.
- EL-SAYED, S.Z. & TURNER, J.T. 1977. Productivity of the Antarctic and tropical/subtropical regions: A comparative study. In DUNBAR, M.J. ed. *Polar Oceans. Proceedings of the SCOR/SCAR Polar Oceans Conference*. Montreal, 463-504.
- EVANS, C.A. & O'REILLY, J.E. 1983. *A handbook for the measurements of chlorophyll *a* in netplankton and nanoplankton. BIOMASS Handbook No.9*. Cambridge: SCAR, 44pp.
- FRYXELL, G.A., JOHANSEN, J.R. & DOUCETTE, G.J. 1982. Phytoplankton cultures around South Georgia. *Antarctic Journal of the United States*, **17**, 160-162.
- HART, T.J. 1934. On the phytoplankton of the southwest Atlantic and the Bellingshausen Sea, 1919-31. *Discovery Reports*, **11**, 1-456.
- HART, T.J. 1942. Phytoplankton periodicity in Antarctic surface waters. *Discovery Reports*, **21**, 261-356.
- HARVEY, H.W. 1947. Fertility of the Ocean. *Proceedings of the Linnean Society London*, **158**, 82-85.
- HOLM-HANSEN, O., EL-SAYED, S.Z., FRANCESCHINI, G.S. & CÜHEL, R.L. 1977. Primary production and the factors controlling growth in the Southern Ocean, In LLANO, G.A. ed. *Adaptations within Antarctic ecosystems. Proceedings of the third SCAR symposium on Antarctic biology*. Washington D.C.: Smithsonian Institution, 11-50.
- KOPCZYŃSKA, E.E. 1981. Periodicity and composition of summer phytoplankton in Ezcurra Inlet, Admiralty Bay, King George Island, South Shetland Islands. *Polish Polar Research*, **2**, 55-70.
- LEVENTER, A. 1991. Sediment trap diatom assemblages from the northern Antarctic Peninsula region. *Deep Sea Research*, **38**, 1127-1143.
- LIDDICOAT, M.I., TIBBITTS, S. & BUTTER, E.I. 1975. The determination of ammonia in seawater. *Limnology and Oceanography*, **20**, 131-213.
- LIGOWSKI, R. 1986. Net phytoplankton of the Admiralty Bay (King George Island, South Shetland Islands) in 1983. *Polish Polar Research*, **7**, 127-154.
- Ligowski, R. 1993. Microphytobenthos. In RAKUSA-SUSZCZEWSKI, S. ed. *The Maritime Antarctic Coastal Ecosystem of Admiralty Bay*. Warsaw: Department of Antarctic Biology, Polish Academy of Science, 53-56.
- LIPSKI, M. 1987. Variations of physical conditions, nutrients and chlorophyll *a* contents in Admiralty Bay (King George Island, South Shetland Islands). *Polish Polar Research*, **8**, 307-332.
- MITCHELL, B.G. & HOLM-HANSEN, O. 1991. Observations and modeling of the Antarctic phytoplankton crop in relation to mixing depth. *Deep Sea Research*, **38**, 981-1007.
- NELSON, D.M. & SMITH, W.O. 1986. Phytoplankton bloom dynamics of the western Ross Sea ice edge - II. Mesoscale cycling of nitrogen and silicon. *Deep Sea Research*, **33**, 1389-1412.
- NÖTHIG, E.M. 1988. On the ecology of the phytoplankton in the southeastern Weddell Sea (Antarctica) in January/February 1985. *Reports on Polar Research*, No. 53, 118pp.
- NOWOSIELSKI, L. 1980. Meteorological conditions at Arctowski Station in 1978 (King George Island, South Shetland Islands). *Polish Polar Research*, **1**, 83-93.
- PERISSINOTTO, R. & DUNCOMBE RAE, C.M. 1990. Occurrence of anticyclonic eddies on the Prince Edward Plateau (Southern Ocean): effects on phytoplankton biomass and production. *Deep Sea Research*, **9**, 777-793.
- PLATT, H.M. 1979. Ecology of King Edward Cove, South Georgia: macrobenthos and the benthic environment. *British Antarctic Survey Bulletin*, No. 49, 231-238.

- PREGO, R., PEREZ, F.F. & FIGUEIRAS, F.G. 1989. Hidrografia de Admiralty Bay, Isla King George, Antartida, al comienzo del verano austral de 1988-89. In *Actas del Tercer Symposium Español de Estudios Antárticos*. Gredos: CSIC, 24-29.
- PRIDDLE, J., HAWES, I., ELLIS-EVANS, J.C. & SMITH, T.J. 1986. Antarctic aquatic ecosystems as habitats for phytoplankton. *Biological Reviews*, **61**, 199-238.
- PRUSZAK, Z. 1980. Currents circulation in the waters of Admiralty Bay (region of Arctowski Station on King George Island). *Polish Polar Research*, **1**, 55-74.
- RAKUSA-SUSZCZEWSKI, S., BATTKE, Z. & CISAK, J. 1993. Morphometry of the Admiralty Bay shores and basin. In RAKUSA-SUSZCZEWSKI, S. ed. *The Maritime Antarctic Coastal Ecosystem of Admiralty Bay*. Warsaw: Department of Antarctic Biology, Polish Academy of Science, 27-30.
- ROMAN, M.R., REEVE, M.R. & FROGGATT, J.L. 1983. Carbon production and export from Biscayne Bay, Florida. 1. Temporal patterns in primary production, seston and zooplankton. *Estuarine Coastal and Shelf Science*, **17**, 45-59.
- SAKSHAUG, R. & HOLM-HANSEN, O. 1984. Factors governing pelagic production in polar seas. In HOLM-HANSEN, O., BOLIS, L. & GILLES, R. eds *Marine Phytoplankton and Productivity*. Berlin: Springer-Verlag, 1-18.
- SEELIGER, U. 1982. Preliminary evaluation of the structure and function of primary producer communities in the Patos Lagoon Estuary (Brazil). *Atlantica*, **5**, 109-110.
- SOMMER, U. 1989. Maximal growth rates of Antarctic phytoplankton: only weak dependence on cell size. *Limnology and Oceanography*, **34**, 1109-1112.
- SPIES, A. 1987. Growth rates of Antarctic marine phytoplankton in the Weddell Sea. *Marine Ecology Progress Series*, **41**, 267-274.
- STRICKLAND, J.D.H. & PARSONS, T. 1972. A practical handbook of sea water analysis, 2nd edn. *Bulletin Fisheries Research Board of Canada*, **167**, 1-310.
- SZAFRANSKI, Z. & LIPSKI, M. 1982. Characteristics of water temperature and salinity at Admiralty Bay (King George Island, South Shetland Islands, Antarctic) during the austral summer 1978/1979. *Polish Polar Research*, **3**, 7-24.
- TATUR, A. & MYRCHA, A. 1983. Changes in chemical composition of waters running off from the penguin rookeries in the Admiralty Bay region (King George Island, South Shetland Islands, Antarctica). *Polish Polar Research*, **4**, 113-125.
- TOKARCZYK, R. 1986. Annual cycle of chlorophyll *a* in Admiralty Bay, 1981-1982 (King George, South Shetlands). *Polskie Archiwum Hydrobiologii*, **33**, 177-188.
- TRÉGUER, P., LINDNER, L., BENNEKOM, A.J. VAN, LEYNAERT, A., PANOUSE, M. & JACQUES, G. 1991. The production of biogenic silica in the Weddell-Scotia Sea measured by ^{32}Si . *Limnology and Oceanography*, **36**, 1217-1227.
- UTERMÖHL, H. 1958. Zur Vervollkommnung der quantitativen Phytoplankton-Methodik. *Mitteilung der Internationale Vereinigung für Theoretische und Angewandte Limnologie*, No. 9, 1-38.
- WÄGELE, J.W. & BRITO, T.A.S. 1990. Die sublitorale Fauna der maritimen Antarktis. Erste Unterwasserbeobachtungen in der Admiralitätsbucht. *Natur und Museum*, **120**, 269-282.